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Into Turbulent Air: Hummingbird Aerodynamic Control in Unsteady Circumstances

Robert Dudley
REGENTS OF THE UNIVERSITY OF CALIFORNIA THE

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Final Report

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14. ABSTRACT
We have completed and published experimental results and analysis pertaining to flight of hummingbirds within variably-sized von Kármán wakes. This work demonstrated high compensatory capacity to maintain stable flight in the face of continous and unpredictable perturbation, and illustrated size-dependence of variance in wing and body motions such that vortices large enough to interact with both wings elicited the greatest changes in roll, pitch, and yaw fluctuations, and also induced major increases in metabolic costs of flight. We have also completed studies of hummingbird hovering flight within a vertical wind tunnel to enable study of the vortex ring state, a well-known problem in helicopter descent. This work evaluated both ascending and descending flight over a range of velocities, and involved analysis of wingbeat

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Final Report, 2013–2016

AFOSR Flow Interactions and Control
Award No. FA9550-13-1-0127

Dr. Robert Dudley
Department of Integrative Biology
University of California, Berkeley
Berkeley, CA 94720

Into Turbulent Air: Hummingbird Aerodynamic Control in Unsteady Circumstances

Objectives:

Research goals of this study were to characterize flight kinematics and energetics of hummingbirds flying within variable-turbulence airstreams, and to analyze energetic, kinematic, and aerodynamic features of vertically ascending and descending flight.

Abstract:

We have completed and published experimental results and analysis pertaining to flight of hummingbirds within variably-sized von Kármán wakes. This work demonstrated high compensatory capacity to maintain stable flight in the face of continous and unpredictable perturbation, and illustrated size-dependence of variance in wing and body motions such that vortices large enough to interact with both wings elicited the greatest changes in roll, pitch, and yaw fluctuations, and also induced major increases in metabolic costs of flight. We have also completed studies of hummingbird hovering flight within a vertical wind tunnel to enable study of the vortex ring state, a well-known problem in helicopter descent. This work evaluated both ascending and descending flight over a range of velocities, and involved analysis of wingbeat kinematics, body postured, and simultaneous energetic expenditure. As part of this study, we also completed analysis of hummingbird kinematic responses to transient vertical gusts and to flight in sheared flows, and have described "shape-shifting" behaviors relevant to the design of microair vehicles.

Accomplishments/new findings:

Work with von Kármán wakes has demonstrated that flight within environmentally associated vortex shedding is an important factor that influences compensatory mechanisms at the scale of hummingbirds. Shed vortices smaller than a wing length have minimal effects on flight kinematics even at higher speeds, whereas those sized similar to or greater than the wing length induce greater variance in wing and body kinematics, particularly at higher speeds (Figure 1). Individuals flying in wakes behind small and medium cylinders also pass through multiple vortices such that torque induced by an initial vortex will, in part, be compensated by a second incoming vortex of opposite rotational sense. Meanwhile, hummingbirds flying behind a large cylinder will encounter only one vortex at a time, and may thus need to disproportionately alter body and tail kinematics to compensate for changes in streamwise and transverse velocities downstream of the large cylinder. Similar results would characterize more complex flows found in natural vegetational canopies, because large turbulent motions will affect birds far more than small ones. This finding suggests that the spatial energy spectrum of environmental turbulence is worth considering relative to MAV flight performance, not simply the velocity variance magnitude which is often reported as 'turbulence intensity'. This research evaluates, for the first

time, direct consequences of heterogeneity of ambient flow fields for flying hummingbirds, which was one of the original goals of the study. Technological implications for the design of MAV's are clear, given that outdoor aerial environments are characterized by a wide range of turbulent conditions for which compensatory kinematics and control responses will be required, in addition to a net increase in the energetic costs of flight.

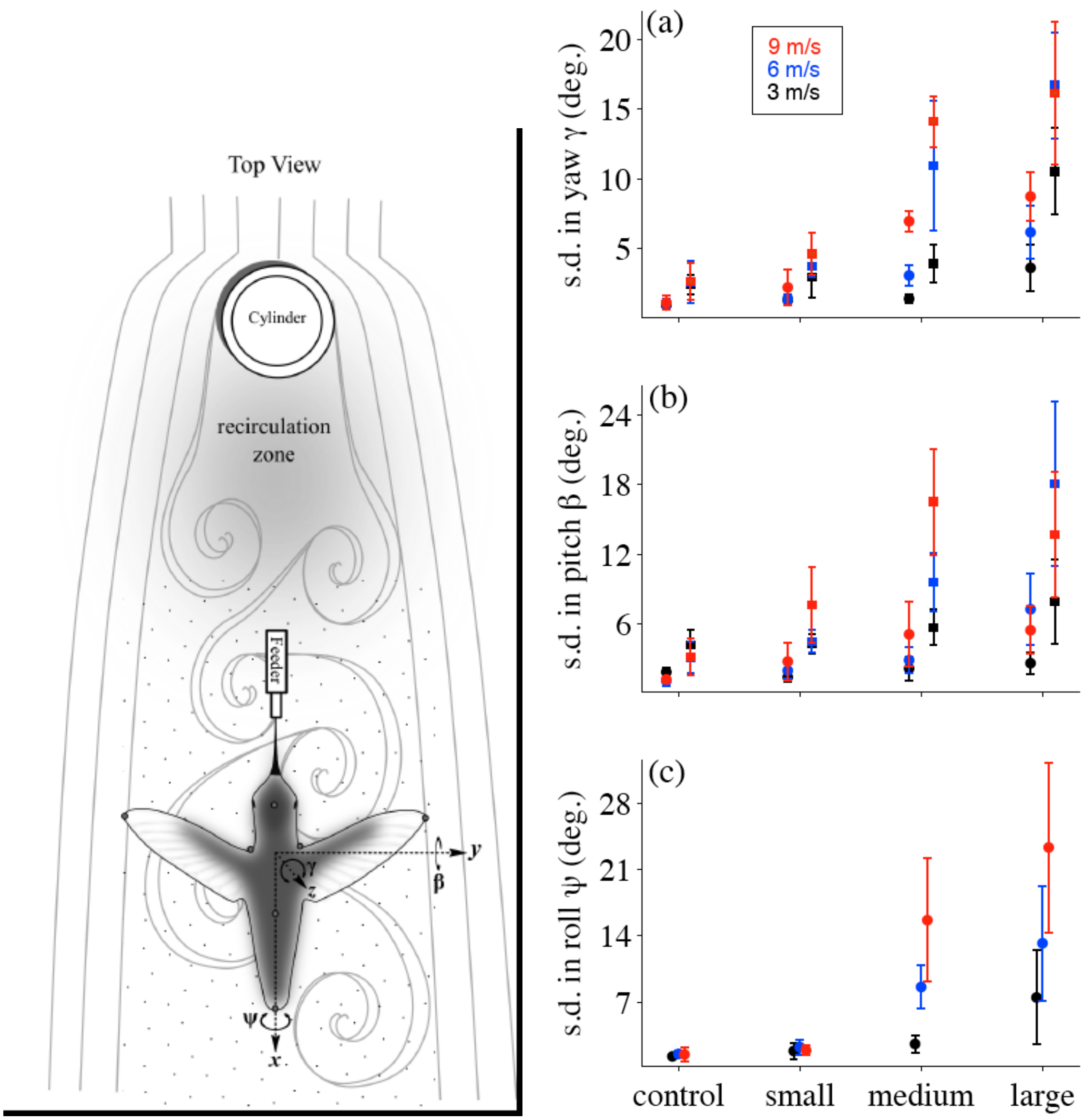

Figure 1. Experimental configuration (left) and body rotational kinematic variation (right) for flight at three airspeeds and with three differently sized cylinders (small, medium, large) generating vortex wakes.

Our work with hummingbirds hovering in a vertical wind tunnel has enabled identification of potential control mechanisms for descending flight in the vortex ring state. Intrugingly, hummingbirds fly stably over a range of upward and downward velocities with no discontinuity in performance. The only systematic indicator of compensation is kinematic variance at the transition from fast to slow descent (~2.5 m/s, near the predicted value for instability at which speed the descent velocity of the bird is comparable to the induced velocity of vortex rings; Figure 2), which may indicate novel control mechanisms for the vortex ring state. This work is the first such study of vertical ascent/descent for any hovering animals, and is of direct relevance to understanding the control of vortex ring state in small-scale aerial vehicles. We currently have a manuscript near-ready for submission to *Journal of the Royal Society Interface* describing these results.

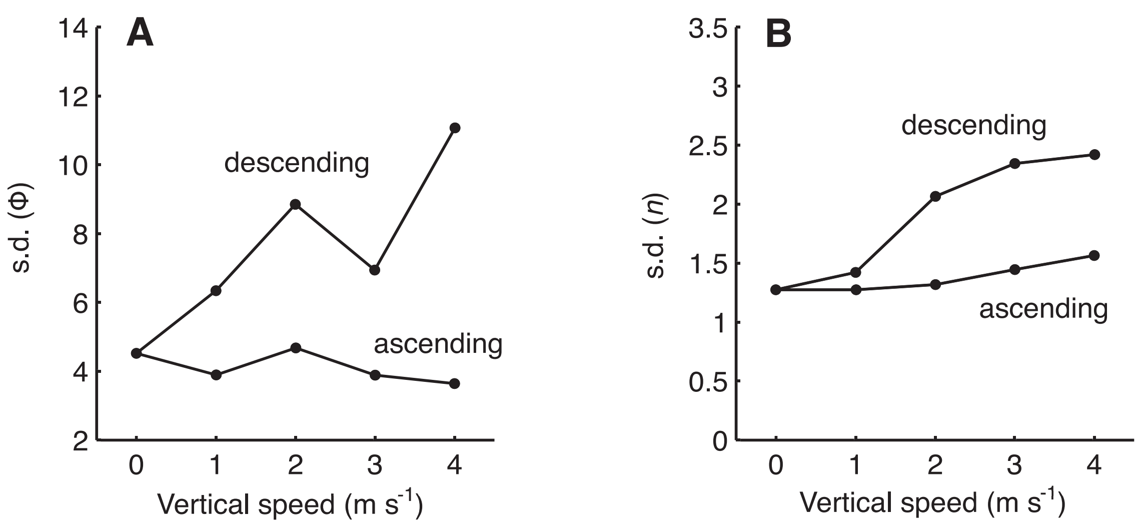

Figure 2. Variance in stroke amplitude (A) and wingbeat frequency (B) for vertically ascending and descending flight of an Anna's Hummingbird, relative to hovering flight (i.e., vertical speed of 0 m/s). Note the discontinuity in stroke amplitude at vertical descent speeds between 2 and 3 m/s, which corresponds to slow descending flight at a speed comparable to the induced velocity. No obvious loss of flight control is evident at any of the studied ascent or descent velocities.

As part of the work on descending flight, we also noticed that hummingbirds could fly in transient vertical gusts, as well as in sheared flows. In the former case, we have documented rapid morphological changes we term "shape-shifting"; the associated manuscript is currently in review at *Proceedings of the National Academy of Sciences USA*. For flight in sheared flow, with the right wing experiencing 10 m/s and the left wing 4 m/s, we documented systematic difference in chord angles between right and left wings through the wingbeat:

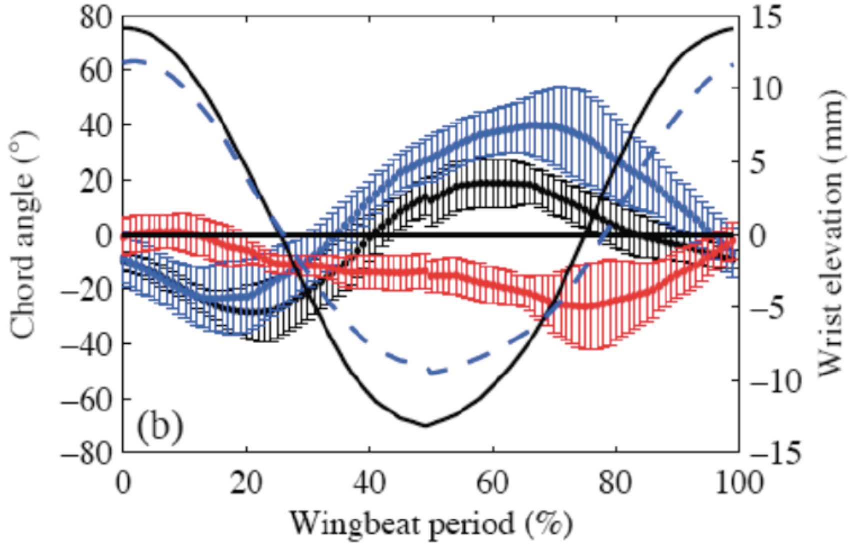

Figure 3. Chord angle of the left wing (in blue), of the right wing (in black) and their difference (in red) through the wingbeat period, with wing stroke amplitude simultaneously plotted (solid line) along with wrist elevation (dashed line), for stable flight in highly sheared flows.

This demonstration of systematic differences in right/left wing angles of attack suggest compensation through independently generated vortex structures on right and left sides of the bird, so as to enable bilaterally asymmetric aerodynamic responses to shear. Our earlier PIV work on flying hummingbirds demonstrated separate vortex rings emanating from each wing, indicating capacity for their independent control and asymmetric force vectoring. In aggregate, our studies of flight in turbulent air, sheared flows, vertical gusts, and in vortex ring state demonstrate that hummingbirds are a premier system for the understanding of flight control on small-scale and high-amplitude aerial perturbations.

Personnel Support:

Robert Dudley (Faculty), Victor Ortega (Postdoc), Erica Kim (Ph.D. student), Marc Badger (Ph.D. student), eight undergraduates

Publications:

Badger, M., Ortega-Jiménez, V., Wang, H. and R. Dudley. (2016). Into rude air: hummingbird flight performance in variable aerial environments. *Philosophical Transactions of the Royal Society of London*, in press.

Kim, E.J., Wolf, M., Ortega-Jimenez, V.M. and R. Dudley. (2014). Hovering performance of Anna's Hummingbirds (*Calypte anna*) in ground effect. *Journal of the Royal Society Interface* **11**:20140505 (8 pp.)

Ortega-Jimenez, V.M., Wolf, M., Variano, E.A. and R. Dudley. (2014). Into turbulent air: size-dependent effects of von Kármán vortex streets on hummingbird flight kinematics and energetics. *Proceedings of the Royal Society B* doi:10.1098/rspb.2014.0180 (10 pp.)

Interactions:

a) Meeting participation

Victor Ortega participated in the 2013 AFOSR Annual Program Review, and in the 2014 Annual Meetings of the Society for Integrative and Comparative Biology. Robert Dudley participated the 2014 and 2015 AFOSR Annual Program Reviews, and in the 2015 and 2016 Annual Meetings of the Society for Integrative and Comparative Biology.

b) Consultative and advisory functions to other laboratories (none)

Technology assists, transitions, and transfers: (none)

New discoveries, inventions, or patent disclosures: (none)

Honors/awards: Erica Kim received her Ph.D. based in part on research supported by this grant.

1.

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Final Report

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Hummingbird Aerodynamic Control in Unsteady Circumstances

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Robert Dudley

Program Manager
The AFOSR Program Manager currently assigned to the award

Yvett Leyva

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04/15/2013

Reporting Period End Date

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Abstract

We have completed and published experimental results and analysis pertaining to flight of hummingbirds within variably-sized von Kármán wakes. This work demonstrated high compensatory capacity to maintain stable flight in the face of continous and unpredictable perturbation, and illustrated size-dependence of variance in wing and body motions such that vortices large enough to interact with both wings elicited the greatest changes in roll, pitch, and yaw fluctuations, and also induced major increases in metabolic costs of flight. We have also completed studies of hummingbird hovering flight within a vertical wind tunnel to enable study of the vortex ring state, a well-known problem in helicopter descent. This work assessed both ascending and descending flight over a range of velocities, and involves analysis of wingbeat kinematics, body postures, and simultaneous energetic expenditure. Finally, we have completed work on gust rejection by flying hummingbirds, and have documented unique kinematic strategies to effect stability during transient perturbation.

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Archival Publications (published) during reporting period:

Badger, M., Ortega-Jiménez, V., Wang, H. and R. Dudley. (2016). Into rude air: hummingbird flight performance in variable aerial environments. Philosophical Transactions of the Royal Society of London, in press.

Kim, E.J., Wolf, M., Ortega-Jimenez, V.M. and R. Dudley. (2014). Hovering performance of Anna's Hummingbirds (Calypte anna) in ground effect. Journal of the Royal Society Interface 11:20140505 (8 pp.)

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2. New discoveries, inventions, or patent disclosures:

Do you have any discoveries, inventions, or patent disclosures to report for this period?

No

Please describe and include any notable dates

Do you plan to pursue a claim for personal or organizational intellectual property?

Changes in research objectives (if any):

none

Change in AFOSR Program Manager, if any:

Doug Smith was the original Program Manager.

Extensions granted or milestones slipped, if any:

none

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
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